An effective combination of magnetic and conductive layers of a magnetically shielded room

K. Yamazaki [1], K. Kato[1], and K. Fujiwara[2]

[1]*Research & Development Institute, Takenaka Corp., 270-1395 Chiba, Japan;*
[2]*Dept. of Electrical and Electronic Eng., Okayama Univ., 700-8530 Okayama, Japan*

1 Introduction

As magnetic fields generated by the human brain and heart are extremely weak, a magnetically shielded room (MSR) must be installed to reduce magnetic noises. Especially in the case of biomagnetic measurements such as the MEG (magneto encephalogram) and the MCG (magneto-cardiogram), of which the signals always exist in the frequency range less than several ten Hz, the following magnetic noises must be reduced by the MSR; noises at less than 1 Hz due to elevators, and noises at several ten Hz due to air conditioners, fans, electric lines and medical equipment.

An analytical expression derived by Wills [1] and an approximate formula by Mager [2] have been used to predict the shielding effect of a MSR. Those formulas, however, cannot calculate the contributions of eddy currents and door construction. The popular MSR designed for biomagnetism is composed of a magnetic material such as permalloy (PC) and conductive materials such as aluminum and copper. The expected effects of those materials are to reduce magnetic noises at less than 1 Hz, at several ten Hz and at the radio frequency, respectively [3]. It is pointed out that the shielding effect at above a few Hz depends on the combination of magnetic and conductive layers [4].

In this paper, the 3-D magnetic field analysis is carried out by using the finite element method taking account of eddy currents [5] to estimate an effective combination of magnetic and conductive layers. The consequences of the analysis can be applied to the optimal design of a MSR in the frequency range from 0.01 Hz to several ten Hz. The numerical simulation is verified by comparing results computed with those measured in terms of the shielding factor and the phase shift of magnetic noises generated by the dc electric railcar nearby. The shielding factor of a MSR composed of only PC layers is also compared with that obtained from the formulas by Wills and Mager for the verification.

2 Methods of analysis and measurement

Figure 1 shows the analyzed model of a MSR, which is composed of three PC layers and one Al layer (PC (inner) - PC (middle) - Al - PC (outer)). The height of the MSR is 3,900 mm. A gap between the wall and the door is assumed to be 1 mm to simulate electric isolation and magnetic connection between them. The incremental permeability and the conductivity of PC are $10^4\,\mu_0$ (μ_0: permeability of vacuum) and 1.63×10^5 S/m, respectively. The conductivity of Al is 3.53×10^6 S/m. The spatial distributions of magnetic noises in MSR's having different layer combinations are computed by using the 3-D magnetic field analysis. The magnetic noises in the frequency range from 0.1 Hz to 10.0 Hz are generated in the y-direction by a pair of 3 m square coil placed near the MSR. The amplitude of the y-component of magnetic noise at the center point O is 6.0×10^{-6} T in the case without the MSR.

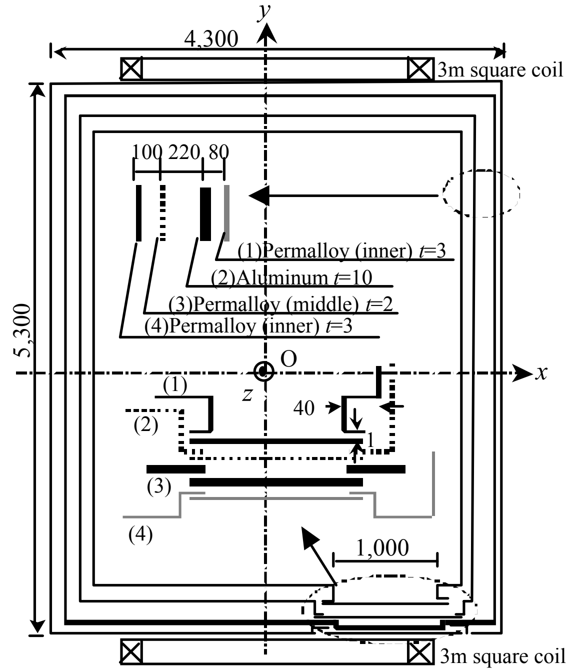

Figure 1: *Analyzed model of magnetically shielded room (full model).*

In the magnetic field analysis, the 3-D finite element method is applied, which employs the magnetic vector potential and hexahedoral edge elements [5].
The shielding factor at the center point O is measured by using a fluxgate magnetometer (Applied Physics Systems, APS520A). The fluctuations of environmental magnetic fields inside and outside the MSR are measured simultaneously by using a SQUID magnetometer and a fluxgate magnetometer, respectively.

3 Results

3.1 Analysis

Figure 2 shows the computed spatial distribution of the y-component of the flux density, By, along the y-axis in the MSR normalized by the applied ampere-turns, nI. Table 1 shows the analyzed and measured frequency dependence of shielding factor at the center point O. Tables 2 and 3 show the effects of the layer combination and the door construction on the shielding factor at the center point O, respectively. Figure 3 shows the computed spatial distribution of flux density vectors at the rear side of the MSR. The frequency is 0.1 Hz. The shielding factor, SF, is defined as a ratio of the flux density in the case with the MSR to that without the MSR.
As shown in Table 1, the SF's at 0.1 and 1.0 Hz obtained from the analysis are about a half of those by the measurement. SF at 10 Hz is almost the same as that by the measurement. The tendency of frequency dependence of SF analyzed is fairly in agreement with those measured. As shown in Table 2, the SF of no. L-7 (outer and inner PC's, spacing: 180 mm) is about twice as large as that of no. L-6 (outer and middle PC's, spacing:100 mm). This difference is due to the contribution of the spacing between two PC layers. On the other hand, the shielding factor, SF_{12}, for a spherical two-layer MSR is derived by Wills [1] and Mager [2] as follows:

$$SF_{12} \approx 1 + SF_1 + SF_2 + SF_1 \cdot SF_2 \cdot \left\{ 1 - (r_1 / r_2)^3 \right\}, \quad (1)$$

where SF_1 and SF_2 are the shielding factors of an inner layer (radius: r_1) and an outer layer (radius: r_2), respectively. Equation (1) says that the shielding factor composed of only PC layers depends on the spacing between them. This tendency coincides with that obtained from the magnetic field analysis. The SF of no. L-14 (outer, middle, inner PC's and Al) is about three times as large as that of no. L-12 (outer, middle and inner PC's). The SF of no. L-2 (only Al) is about 1, which means there is no shielding effect at 0.1 Hz. On the other hand, the SF of no. L-10 (outer and middle PC's, and Al) is about twice as large as that of no. L-6 (outer and middle PC's). This

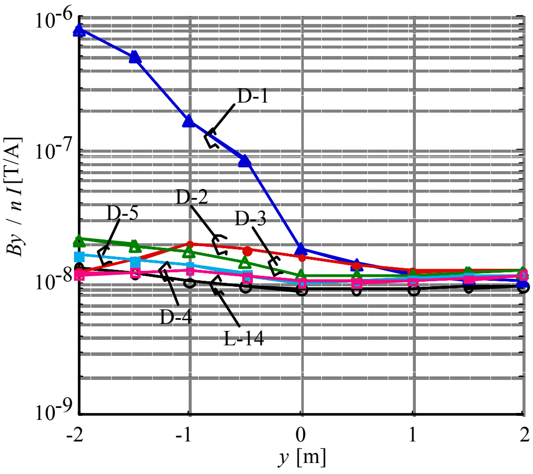

Figure 2: *Spatial distribution of y-component of flux density along y-axis (0.1 Hz, computed).*

Table 1: *Analyzed and measured frequency dependence of shielding factor at shielded room (full model)*

frequency [Hz]	0,1	1.0	10.0
analyzed SFy	91,7	939,6	24232,1
measured SFy	192,3	2272,7	31249,9

Table 2: *Effect of layer combination on shielding factor at the center point (0.1 Hz, computed).*

layer / no.	outer PC (t = 2 mm)	Al (t = 10 mm)	middle PC (t = 2 mm)	inner PC (t = 3 mm)	SFy	phase
L-1	>				5,92	-0,602
L-2		>			1,03	-16,529
L-3			>		5,95	-0,686
L-4				>	8,64	-1,361
L-5	>	>			6,25	-19,266
L-6	>		>		15,07	-1,811
L-7	>			>	25,45	-2,753
L-8		>	>		6,96	-34,359
L-9			>	>	15,75	-3,148
L-10	>	>	>		33,35	-64,816
L-11	>	>		>	47,83	-61,696
L-12	>		>	>	36,2	-4,930
L-13		>	>	>	18,66	-37,062
L-14	>	>	>	>	91,67	-70,922

Table 3: *Effect of door construction on shielding factor at the center point (0.1 Hz, computed).*

door / no.	outer PC (t = 2 mm)	Al (t = 10 mm)	middle PC (t = 2 mm)	inner PC (t = 3 mm)	SFy
D-1					52,36
D-2		>			51,86
D-3		>		>	70,82
D-4	>	>			79,75
D-5		>	>	>	81,91

indicates that the Al layer itself can increase the shielding effect by the PC-Al-PC sandwiched combination. It is supposed that the eddy current effect of the Al layer is increased by the concentration of magnetic flux by the PC layers at both sides of the Al layer. As shown in Figure 3, the flux density vectors of no. L-10 with the Al layer are smaller than those of no. L-6 without the Al layer. This is due to the eddy current effect of the Al layer. When a MSR having three layers composed of two PC layers and one Al layer is designed taking account of a low cost, a sandwiched PC-Al-PC combination is optimal.

As regards the door, the Al door is required to shield the electromagnetic field at the high frequency of 1 MHz, because operation of a SQUID magnetometer is affected by the RF field [6]. Therefore, the layer combination of door must be discussed under the condition that the Al door is included. The magnetic and electric connections between the wall and the door depend on the number of PC layers, which means the weight of a door. Therefore, it is required that the number of PC layers of the door is decreased. It also results in a low cost. As shown in Figure 2, the magnetic noise at the door side (y<0) in the case of the Al and inner PC doors (no. D-3) is larger than that in the case of the Al and outer PC doors (no. D-4). This indicates that the outer PC door is more effective to reduce leakage magnetic fields from the door than the inner PC door. The *SF* in the case of the only Al door (no. D-2) is about a half of that in the case of all the doors (no. L-14). The *SF* of no. D-4 is a little smaller than that of no. L-14, and is almost the same as that in the case of the Al, inner and middle PC doors (no. D-5). From the standpoint of the door construction, no. D-4 is supposed to be optimal.

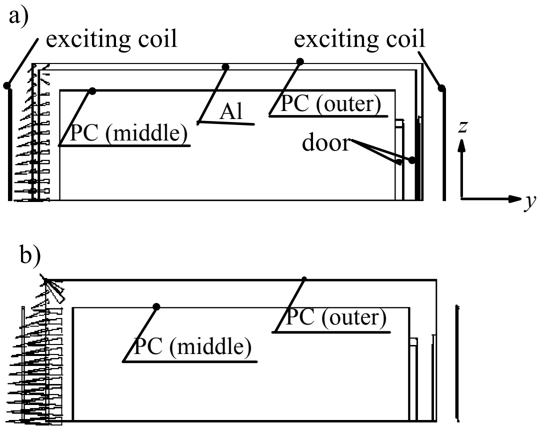

Figure 3: *Spatial distribution of flux density vectors with and without Al layer (0.1 Hz, z-y plane, x=0, computed). a)no. L-10 (PC(middle) - Al - PC(outer)), b) no. L-6 (PC(middle) - PC(outer).*100 mm).

3.2 Measurement of inside and outside of actually installed MSR

Figure 4 shows the fluctuations of magnetic fields in the vertical direction inside and outside the MSR (no. L-14) which was installed measured by using a SQUID magnetometer (Seiko Instruments) and a fluxgate magnetometer, respectively. The *SF* of about 115 between them can be obtained as a ratio of the magnitude of fluctuation of flux density in the case with the MSR to that without the MSR. The *SF* is not so different from the *SF* of 91, which was obtained by the analysis as shown in Table.2. On the other hand, when the fluctuation of the magnetic field inside the MSR shifts for 2.4 sec, the maximum coefficient of correlation 0.93 is obtained between the magnetic fields inside and outside the MSR. The time difference of 2.4 sec is equivalent to the phase shift of 86 degree in case of 0.1 Hz. This tendency is very similar to that obtained from the analysis as shown in Table.2.

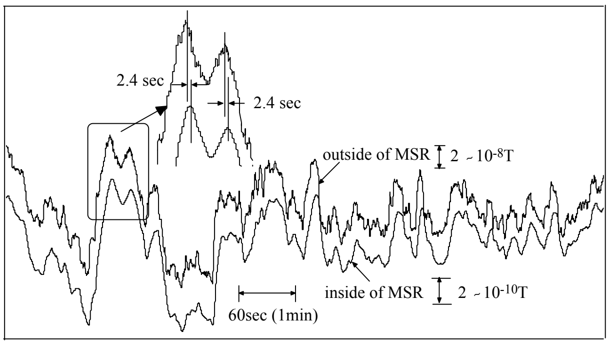

Figure 4: *Fluctuations of magnetic fields in the vertical direction inside and outside of MSR of no. L-14 (PC(inner) - PC(middle) - Al - PC(outer)) measured by SQUID magnetometer and fluxgate-magnetometer, respectively.*

4 Conclusion

An effective combination of magnetic and conductive layers of wall and door for the optimal design of a MSR is estimated by using the 3-D magnetic field analysis taking account of eddy currents. The method of analysis is verified by comparing the frequency dependence of the shielding factor computed with that measured, and by comparing the effect of the spacing between the PC layers computed with that obtained from the formulas by Wills and Mager. An Al layer itself can increase the shielding effect by a sandwiched PC-

Al-PC combination even at frequencies at which only Al layer has no shielding effect. As regards the door construction, the door composed by the Al and outer PC layers is supposed to be optimal. The analyzed results on the shielding effect and the phase shift are validated by the measurements of magnetic noises inside and outside an actually installed MSR, which is supposed to be generated by the dc electric railcar nearby.

References

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